*Chem. Eur. J.* **2004**

Supporting Information

for

# Palladium-Catalyzed Intramolecular Oxidative Alkylation of 4-Pentenyl β-Dicarbonyl Compounds

Cong Liu, Xiang Wang, Tao Pei, and Ross A. Widenhoefer*[a]

[a] C. Liu, Dr. X. Wang, Dr. T. Pei, and Prof. R. A. Widenhoefer
P. M. Gross Chemical Laboratory, Duke University
Durham, North Carolina 27708–0346 (USA)

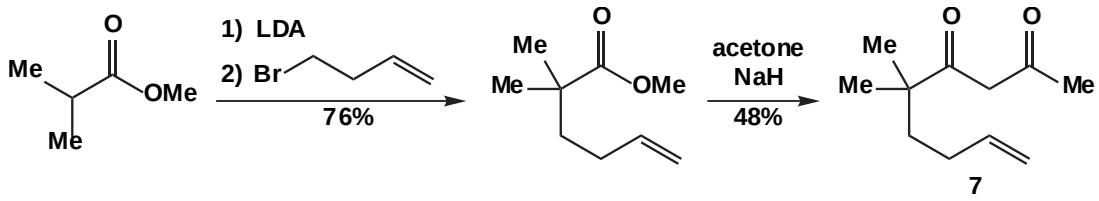
This Supporting Information contains experimental procedures, analytical and spectroscopic data for cyclohexenones, and alkenyl β-dicarbonyl compounds (26 pages).

## Experimental

**General Methods**. Catalytic reactions were performed under an atmosphere of dry nitrogen. NMR spectra were obtained on a Varian spectrometer operating at 400 MHz for $^{1}H$ NMR and 100 MHz for $^{13}C$ NMR in $CDCl_3$ unless otherwise noted. IR spectra were obtained on a Bomen MB-100 FT IR spectrometer. Gas chromatography was performed on a Hewlett-Parkard 5890 gas chromatography equipped with a 25 m polydimethylsiloxane capillary column. Flash column chromatography was performed employing 200-400 mesh silica gel (EM). Thin layer chromatography (TLC) was performed on silica gel 60 $F_{254}$ eluting with a 5:1 mixture of hexanes and ethyl acetate unless otherwise noted. Elemental analyses were performed by Complete Analysis Laboratories (Parsippany, NJ). 1,4-Dioxane (Aldrich, anhydrous) was used as received. $PdCl_2(CH_3CN)_2$ (**2**) was purchased (Strem) or was prepared from $PdCl_2$ (Strem) employing a literature procedure.[1] 8-Nonene-2,4-dione (**4**)[2], 1-phenyl-7-octene-1,3-dione (**11**)[3], 5-bromo-3,3-dimethyl-1-pentene[4], and 5-hexynal[5] were prepared according to published procedures. All other reagents were purchased from major chemical suppliers and were used as received.

## Alkenyl β-diketones

**5,5-Dimethyl-8-nonene-2,4-dione (7).** Dione **7** was synthesized in two steps in 36% overall yield from methyl isobutyrate as outlined in Scheme S1.




**Scheme S1**

A solution of methyl isobutyrate (5.0 g, 49 mmol) in THF (15 mL) was added slowly to a solution of LDA [generated from *n*-BuLi (21 mL in hexanes, 2.5 M, 52 mmol) and diisopropylamine (5.5 g, 54 mmol) in THF (65 mL)] at –78 °C and stirred for 20 min. The resulting solution was treated with a solution of 4-bromo-1-butene (7.4 g, 55 mmol) in HMPA (10 mL) and stirred at –78 °C for 12 h. The

reaction mixture was quenched with aqueous HCl (1 N, 30 mL), the layers were separated, and the aqueous layer was extracted with ether (3 × 50 mL). The combined organic extracts were washed with water (4 × 20 mL) and saturated aqueous $NaHCO_3$ (2 × 20 mL), dried ($MgSO_4$), and concentrated under vacuum. Distillation (64 °C, 50 mm Hg) gave methyl 2,2-dimethyl-5-hexenoate (5.8 g, 76%) as a colorless oil.

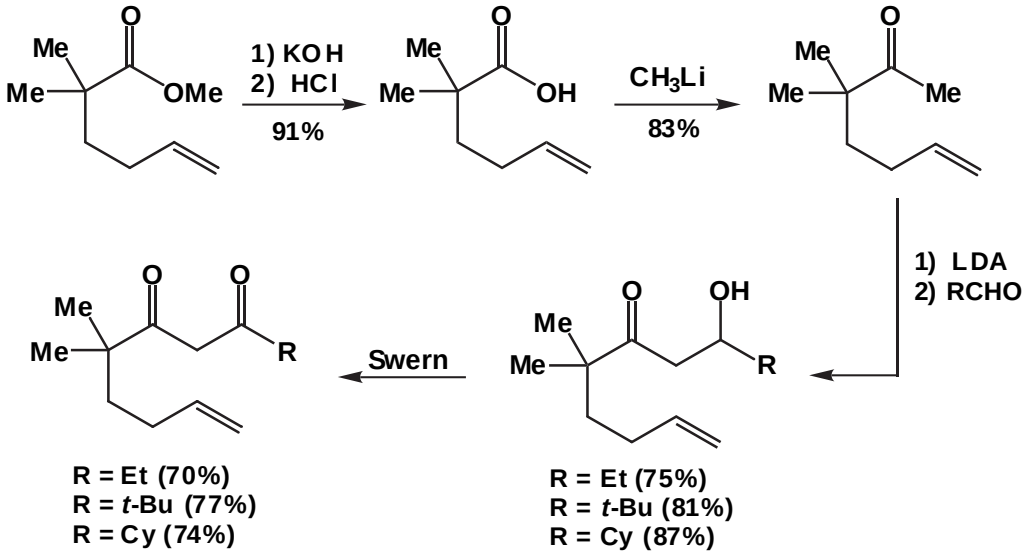
A suspension of methyl 2,2-dimethyl-5-hexenoate (3.1 g, 20 mmol) and NaH (2.0 g, 83.3 mmol) in ether (50 mL) and DMF (30 mL) was heated at 70 °C for 1 h. The resulting mixture was cooled to 0 °C and water (30 mL) and aqueous HCl (2 N, 20 mL) were added sequentially. The layers were separated and the aqueous layer was extracted with ether (3 × 50 mL). The combined organic extracts were washed (brine), dried ($MgSO_4$), and concentrated under vacuum. Chromatography of the residue ($SiO_2$; hexanes–ether = 50:1 → 30:1) gave **2** (1.75 g, 48%) as a colorless oil.

**For methyl 2,2-dimethyl-5-hexenoate:**[6] $^1$H NMR: δ 5.76 (tdd, J = 6.4, 10.4, 16.8 Hz, 1 H), 4.89-5.01 (m, 2 H), 3.64 (s, 3 H), 1.93-2.00 (m, 2 H), 1.58-1.62 (m, 2 H), 1.17 (s, 6 H). $^{13}$C{$^1$H} NMR: δ 178.4, 138.6, 114.6, 51.8, 42.2, 40.0, 29.5, 25.3.

**For 5,5-dimethyl-8-nonene-2,4-dione (7):** Enol:keto = 20:1. $^1$H NMR: δ 15.8 (br s, 1 H), 5.75 (tdd, *J* = 6.4, 10.0, 16.8 Hz, 1 H), 5.57 (s, 1 H), 4.88-5.00 (m, 2 H), 2.05 (s, 3 H), 1.89-1.96 (m, 2 H), 1.55-1.60 (m, 2 H), 1.12 (s, 6 H). $^{13}$C{$^1$H} NMR: δ 199.4, 192.5, 138.8, 114.5, 96.9, 42.4, 40.0, 29.2, 25.6, 25.3. IR (neat, $cm^{-1}$): 2973, 2940, 1650, 1600, 1473. TLC: $R_f$ = 0.72. Anal. calcd (found) for $C_{11}H_{18}O_2$: H, 9.95 (9.95); C, 72.49 (72.44).

**2,2-Dimethyl-9-decene-3,5-dione (Table 1, entry 2).** 2,2-Dimethyl-9-decene-3,5-dione was isolated in 27% yield as a colorless oil by vacuum distillation (58 °C, 250 mTorr) from reaction of 5,5-dimethyl-hexane-2,4-dione and 4-bromo-1-butene employing a procedure similar to that used to synthesize 6-methyl-9-decene-3,5-dione (see below). Enol:keto = 19:1. $^1$H NMR: δ 15.9 (br s, 1 H), 5.78 (tdd, *J* = 6.8, 10.2, 16.8 Hz, 1 H), 5.58 (s, 1 H), 4.97-5.05 (m, 2 H), 2.31 (t, *J* = 7.6 Hz, 2 H), 2.09 (q, *J* = 7.6 Hz, 2 H), 1.71 (quint, *J* = 7.6 Hz, 2 H), 1.16 (s, 9 H). $^{13}$C{$^1$H} NMR: δ 200.5, 195.4, 138.1, 115.5, 95.4, 39.2, 38.2, 33.3, 27.5, 25.0. IR (neat, $cm^{-1}$): 2976, 2935, 1604, 1455. TLC: $R_f$ = 0.83. Anal. calcd (found) for $C_{12}H_{20}O_2$: H, 10.27 (10.16); C, 73.43 (73.28).

**6,6-Dimethyl-9-decene-3,5-dione (Table 1, entry 7, 8).** 6,6-Dimethyl-9-decene-3,5-dione was isolated in 40% overall yield from methyl 2,2-dimethyl-5-hexenoate employing the procedure outlined in Scheme S2. The aldol addition and Swern oxidation were performed according to a published procedure.[7]




**Scheme S2**

A solution of methyl 2,2-dimethyl-5-hexenoate (5.8 g, 37 mmol) and KOH (8.0 g, 143 mmol), in a water (25 mL)/THF (30 mL)/methanol (80 mL) mixture was stirred at 25 °C for 1 h and 40 °C for 1 h. The resulting mixture was treated with ice (40 g) and acidified (pH = 1) by slow addition of concentrated hydrochloric acid (25 mL). The layers were separated and the aqueous layer was extracted with ether (4 × 100 mL). The combined organic extracts were washed (brine), dried ($MgSO_4$), and concentrated under vacuum. Distillation (65 °C, 200 mTorr) of the residue gave 2,2-dimethyl-5-hexenoic acid (4.8 g, 91%) as a colorless oil.

A THF solution of methyl lithium (97 mL, 1.4 M, 136 mmol) was added to a solution of 2,2-dimethyl-5-hexenoic acid in THF (100 mL) at 0 °C, stirred for 3 h, and quenched by sequential addition of $Me_3SiCl$ (50 mL, 37 mmol), aqueous HCl (3 N, 20 mL), and ice (100 g). The layers were separated and the aqueous layer was extracted with ether (3 × 100 mL). The combined organic extracts were washed

(brine), dried ($MgSO_4$), and concentrated under vacuum. Distillation of the residue (60-65 °C, 50 mm Hg) gave 3,3-dimethyl-6-hepten-2-one (3.6 g, 83%) as a colorless oil.

3,3-Dimethyl-6-hepten-2-one (2.0 g, 11 mmol) was added slowly to a solution of LDA [generated from *n*-BuLi (3.8 mL, 2.5 M, 9.5 mmol) and diisopropylamine (1.0 g, 9.5 mmol) in THF (20 mL)] at –78 °C and stirred for 15 min. Propionaldehyde (0.55 g, 9.5 mmol) was added dropwise to the resulting white suspension and stirred for 1 h. The resulting mixture was quenched with saturated aqueous ammonium chloride (6 mL) at –78 °C, warmed to room temperature, and extracted with ether (200 mL). The ether extract was washed with brine and the combined aqueous fractions were extracted with ether ($2 \times 30$ mL). The combined organic extracts were washed (brine), dried ($MgSO_4$), and concentrated under vacuum. Chromatography of the residue ($SiO_2$; hexanes–ether = 10:1 $\rightarrow$ 1:2) gave 3-hydroxy-6,6-dimethyl-9-decene-5-one (1.2 g, 75%) as a colorless oil.

Solutions of DMSO (0.83 mL, 12 mmol) in $CH_2Cl_2$ (2 mL) and 3-hydroxy-6,6-dimethyl-9-decene-5-one (1.1 g, 5.4 mmol) in $CH_2Cl_2$ (3 mL) were added sequentially to a solution of oxalyl chloride (0.51 mL, 5.8 mmol) in $CH_2Cl_2$ (10 mL) at –78 °C, stirred for 1.5 h, and then treated with triethylamine (5 g, 50 mmol). The resulting solution was stirred for 10 min, warmed to room temperature, and treated with water (10 mL). The layers were separated and the aqueous layer was extracted with ether ($3 \times 50$ mL). The combined organic extracts were washed with aqueous HCl (1 N, $2 \times 10$ mL) and saturated aqueous $NaHCO_3$ ($2 \times 10$ mL), dried ($MgSO_4$), and concentrated under vacuum. Chromatography of the residue ($SiO_2$; hexanes–ether = 50:1 $\rightarrow$ 25:1) gave 6,6-dimethyl-7-decene-3,5-dione (0.73 g, 70%) as a colorless oil.

**For 2,2-dimethyl-5-hexenoic acid:**[8] $^1$H NMR: $\delta$ 5.78 (tdd, $J$ = 6.3, 10.2, 16.5 Hz, 1 H), 4.91-5.04 (m, 2 H), 2.00-2.07 (m, 2 H), 1.60-1.66 (m, 2 H), 1.20 (s, 6 H). $^{13}C\{^1H\}$ NMR: $\delta$ 184.2, 137.6, 113.9, 41.3, 38.8, 28.5, 24.2. Anal. calcd (found) for $C_8H_{14}O_2$: H, 9.92 (9.81); C, 67.57 (67.42).

**For 3,3-dimethyl-6-hepten-2-one:**[9] $^1$H NMR (300 MHz): $\delta$ 5.73 (tdd, $J$ = 6.3, 9.9, 16.8 Hz, 1 H), 4.88-4.99 (m, 2 H), 2.07 (s, 3 H), 1.84-1.96 (m, 2 H), 1.53-1.59 (m, 2 H), 1.08 (s, 6 H). $^{13}C\{^1H\}$ NMR (75 MHz): $\delta$ 213.0, 137.6, 113.9, 46.9, 38.3, 28.4, 24.4, 23.6. Anal. calcd (found) for $C_9H_{16}O$: H, 11.50 (11.39); C, 77.09 (76.97).

**For 3-hydroxy-6,6-dimethyl-9-decene-5-one:** $^1$H NMR (300 MHz): δ 5.66-5.80 (m, 1 H), 4.89-5.00 (m, 2 H), 3.85-3.95 (m, 1 H), 3.28 (d, *J* = 2.7 Hz, 1 H), 2.60-2.27 (m, 1 H), 2.46 (m, 1 H), 1.85-1.93 (m, 2 H), 1.36-1.63 (m ,4 H), 1.10 (s, 6 H), 0.92 (t, *J* = 7.5 Hz, 3 H). $^{13}$C{$^1$H} NMR (75 MHz): δ 216.7, 137.5, 114.0, 68.4, 46.9, 42.9, 42.3, 38.3, 28.6, 28.3, 23.5, 9.3. IR (neat, cm$^{-1}$): 3445, 2969, 2933, 1696. TLC: $R_f$ = 0.24. Anal. calcd (found) for $C_{12}H_{22}O_2$: H, 11.18 (10.92); C, 72.68 (72.51).

**For 6,6-dimethyl-9-decene-3,5-dione:** Enol:keto = 12:1. $^1$H NMR: δ 15.8 (s, 1 H), 5.77 (tdd, *J* = 6.4, 10.0, 16.8 Hz, 1 H), 5.57 (s, 1 H), 4.90-5.01 (m, 2 H), 3.34 (q, *J* = 7.6 Hz, 2 H), 1.91-1.97 (m, 2 H), 1.57-1.62 (m, 2 H), 1.14 (s, 6 H), 1.13 (t, *J* = 7.6 Hz, 3 H). $^{13}$C{$^1$H} NMR: δ 198.9, 196.9, 138.8, 114.5, 95.6, 42.3, 40.0, 32.2, 29.3, 25.4, 9.9. IR (neat, cm$^{-1}$): 2974, 2939, 1600, 1460. TLC: $R_f$ = 0.74. Anal. calcd (found) for $C_{12}H_{20}O_2$: H, 10.27 (10.13); C, 73.43 (73.21).

**2,6,6-Trimethyl-9-decene-3,5-dione (Table 1, entry 9, 10).** 2,6-Dimethylheptane-3,5-dione (2.0 g, 12.8 mmol), a solution of *n*-BuLi in hexanes (2.5 M, 5.1 mL, 12.8 mmol), and 4-bromo-1-butene (3.2 g, 24 mmol) were added sequentially to a suspension of NaH in THF (30 mL) at 0 °C. The reaction mixture was stirred overnight and then quenched with saturated aqueous $NH_4Cl$ and aqueous HCl (2 N, 10 mL). The layers were separated and the aqueous layer was extracted with ether (3 × 30 mL). The combined organic extracts were washed (brine), dried ($MgSO_4$), and concentrated under vacuum. Distillation of the residue (50 °C, 300 mm Hg) gave 2,6,6-trimethyl-9-decene-3,5-dione (1.34 g, 50%) as a colorless oil. Enol:keto = 10:1. $^1$H NMR: δ 15.9 (br s, 1 H), 5.77 (tdd, *J* = 6.4, 10.0, 16.8 Hz, 1H), 5.59 (s, 1 H), 4.90-5.01(m, 2 H), 2.48 (septet, *J* = 6.8 Hz, 1 H), 1.92-1.98 (m, 2 H), 1.57-1.62 (m, 2 H), 1.14 (d, *J* = 6.8 Hz, 6 H), 1.4 (s, 6 H). $^{13}$C{$^1$H} NMR: δ 200.0, 199.8, 138.8, 114.5, 94.2, 42.5, 40.1, 37.3, 25.4, 19.6. IR (neat, cm$^{-1}$): 2968, 2872, 1594, 1466. TLC: $R_f$ = 0.75. Anal. calcd (found) for $C_{13}H_{22}O_2$: H, 10.54 (10.46); C, 74.24 (74.21).

**2,2,6,6-Tetramethyl-9-decene-3,5-dione (Table 1, entry 11, 12).** 2,2,6,6-Tetramethyl-9-decene-3,5-dione was isolated in 62% overall yield in two steps from 3,3-dimethyl-6-hepten-2-one employing a procedure similar to that described for the synthesis of 6,6-dimethyl-9-decene-3,5-dione (Scheme S2).

**For 3-hydroxy-2,2,6,6-tetramethyl-9-decene-5-one:** $^1$H NMR: δ 5.79 (tdd, *J* = 6.8, 10.0 16.8 Hz, 1 H), 4.91-5.02 (m, 2 H), 3.64 (dd, *J* = 1.2, 10.0 Hz, 1 H), 3.16 (br s, 1 H), 2.69 (dd, *J* = 1.6, 17.2 Hz, 1

H), 3.38 (dd, $J$ = 2.0, 17.2 Hz, 1 H), 1.84-2.00 (m, 2 H), 1.58-1.62 (m, 2 H), 1.13 (s, 3 H), 1.12 (s, 3 H), 0.90 (s, 9 H). $^{13}C\{^{1}H\}$ NMR: δ 218.1, 138.4, 114.9, 75.2, 48.1, 39.3, 38.5, 34.4, 29.2, 25.9, 24.4. IR (neat, $cm^{-1}$): 3545, 2960, 2871, 1697, 1472. TLC: $R_f$ = 0.45. Anal. calcd (found) for $C_{14}H_{26}O_2$: H, 11.58 (11.49); C, 74.29 (74.37).

**For 2,2,6,6-tetramethyl-9-decene-3,5-dione:** Enol:keto ≥ 30:1. $^{1}H$ NMR: δ 16.2 (s, 1 H), 5.77 (tdd, $J$ = 6.4, 10.0, 17.2 Hz, 1 H), 5.71 (s, 1 H), 4.8-5.08 (m, 2 H), 1.92-1.99 (m, 2 H), 1.58-1.62 (m, 2 H), 1.17 (s, 9 H), 1.15 (s, 6 H). $^{13}C\{^{1}H\}$ NMR: δ 201.6, 200.5, 138.9, 114.5, 91.9, 42.8, 40.1, 39.6, 29.3, 27.6, 25.5. IR (neat, $cm^{-1}$): 2970, 2942, 1601, 1470. TLC: $R_f$ = 0.87. Anal. calcd (found) for $C_{14}H_{24}O_2$: H, 10.78 (10.69); C, 74.95 (75.01).

**1-Cyclohexyl-4,4-dimethyl-7-octene-1,3-dione (Table 1, entry 13)**. 1-Cyclohexyl-4,4-dimethyl-7-octene-1,3-dione was isolated in 64% overall yield in two steps from 3,3-dimethyl-6-hepten-2-one employing a procedure similar to that used for the synthesis of 6,6-dimethyl-9-decene-3,5-dione (Scheme S2).

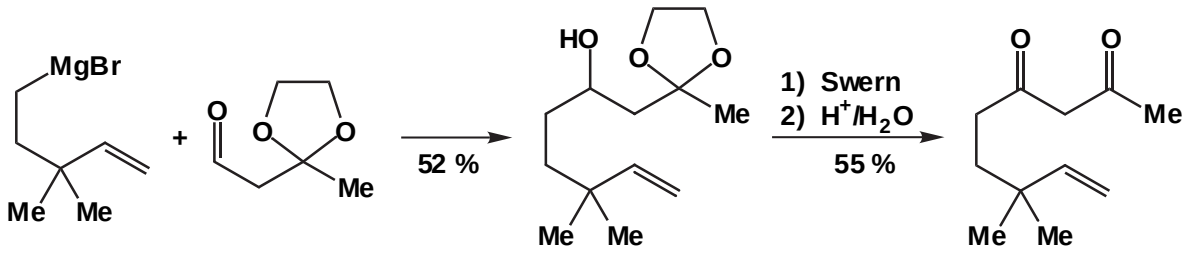
**For 1-Cyclohexyl-1-hydroxy-4,4-dimethyl-7-octene-3-one:** $^{1}H$ NMR (300 MHz): δ 5.71 (tdd, $J$ = 6.3, 10.2, 16.2 Hz, 1 H), 4.87-4.98 (m, 2 H), 3.71 (br s, 1 H), 2.40-2.49 (m, 1 H), 2.60-2.66 (m, 1 H), 1.83-1.90 (m, 2 H), 1.69-1.75 (m, 2 H), 1.53-1.63 (m, 4 H), 0.94-1.30 (m, 7 H), 1.08 (s, 6 H). $^{13}C\{^{1}H\}$ NMR: δ 217.0, 137.5, 114.0, 71.0, 47.0, 42.2, 39.8, 38.3, 28.3, 27.6, 25.8, 25.5, 25.4, 23.5. IR (neat, $cm^{-1}$): 3507, 2925, 2852, 1696, 1641. TLC: $R_f$ = 0.31. Anal. calcd (found) for $C_{11}H_{16}O_2$: H, 11.18 (11.12); C, 76.14 (76.07).

**For 1-Cyclohexyl-4,4-dimethyl-7-octene-1,3-dione:** Enol:keto = 20:1. $^{1}H$ NMR: δ 16.0 (s, 1 H), 5.77 (tdd, $J$ = 6.4, 10.0, 15.2 Hz, 1 H), 5.58 (s, 1 H), 4.98 (qd, $J$ = 1.6, 17.2 Hz, 1 H), 4.91 (tdd, $J$ = 1.2, 2.0, 10.4 Hz, 1 H), 2.19 (tt, $J$ = 3.2, 11.6 Hz, 1 H), 1.91-1.98 (m, 2 H), 1.78-1.87 (m, 4 H), 1.66-1.70 (m, 1 H), 1.57-1.60 (m, 2 H), 1.18-1.43 (m, 5 H), 1.14 (s, 6 H). $^{13}C\{^{1}H\}$ NMR: δ 200.4, 198.6, 138.9, 114.5, 94.5, 47.2, 42.6, 40.1, 29.8, 29.3, 26.0, 25.4. IR (neat, $cm^{-1}$): 2930, 2855, 1620, 1597, 1450. TLC: $R_f$ = 0.50. Anal. calcd (found) for $C_{16}H_{26}O_2$: H, 10.47 (10.58); C, 76.75 (76.59).

**6-Methyl-9-decene-3,5-dione (Table 1, entry 14, 15)**. 6-Methyl-9-decene-3,5-dione was isolated in 33 % yield as a colorless oil from reaction of 3,5-heptadione and 4-bromo-1-butene after

vacuum distillation (70 °C, 50 mm Hg) employing a procedure similar to that used to synthesize 2,6,6-trimethyl-9-decene-3,5-dione. Enol:keto = 5:1. $^1$H NMR: δ 15.5 (br s, 1 H), 5.72-5.82 (m, 1 H), 5.47 (s, 1 H), 4.94-5.03 (m, 2 H), 2.32 (q, *J* = 7.6 Hz, 2 H), 2.04 (q, *J* = 7.6 Hz, 2 H), 1.69-1.78 (m, 1 H), 1.41-1.51 (m, 1 H), 1.05-1.15 (m, 7 H). $^{13}$C{$^1$H} NMR: δ 197.3, 196.5, 138.3, 115.1, 97.7, 41.7, 33.3, 31.9, 31.6, 17.7, 9.8. IR (neat, cm$^{-1}$): 2975, 2935, 1603, 1454, 911. TLC: $R_f$ = 0.78. Anal. calcd (found) for $C_{11}H_{18}O_2$: H, 9.95 (10.03); C, 72.49 (72.38).

**7,7-Dimethyl-8-nonene-2,4-dione (Table 1, entry 16).** 7,7-Dimethyl-8-nonene-2,4-dione was synthesized in 29% overall from (2-methyl-[1,3]-dioxolan-2-yl)acetaldehyde[10] yield employing the procedure depicted in Scheme S3.




**Scheme S3**

5-Bromo-3,3-dimethyl-1-pentene (0.73 g, 4.5 mmol) was added dropwise to a suspension of magnesium turnings (0.24 g, 10.0 mmol) in ether (25 mL). Following complete addition of the alkyl halide, the resulting suspension was refluxed for 20 min and cooled to room temperature. (2-Methyl-[1,3]dioxolan-2-yl)acetaldehyde (0.52 g, 4.0 mmol) was added dropwise and the resulting suspension was stirred at room temperature for 5 h, quenched with saturated aqueous $NH_4Cl$. The layers were separated and the aqueous layer was extracted with ether (3 × 30 mL). The combined organic extracts were washed (brine), dried ($MgSO_4$), and concentrated under vacuum. Chromatography of the residue ($SiO_2$; hexanes-ether = 25:1 → 5:1) gave 5,5-dimethyl-1-(2-methyl-[1,3]-dioxolan-2-yl)-hept-6-en-2-ol (0.47 g, 52%) as a colorless oil.

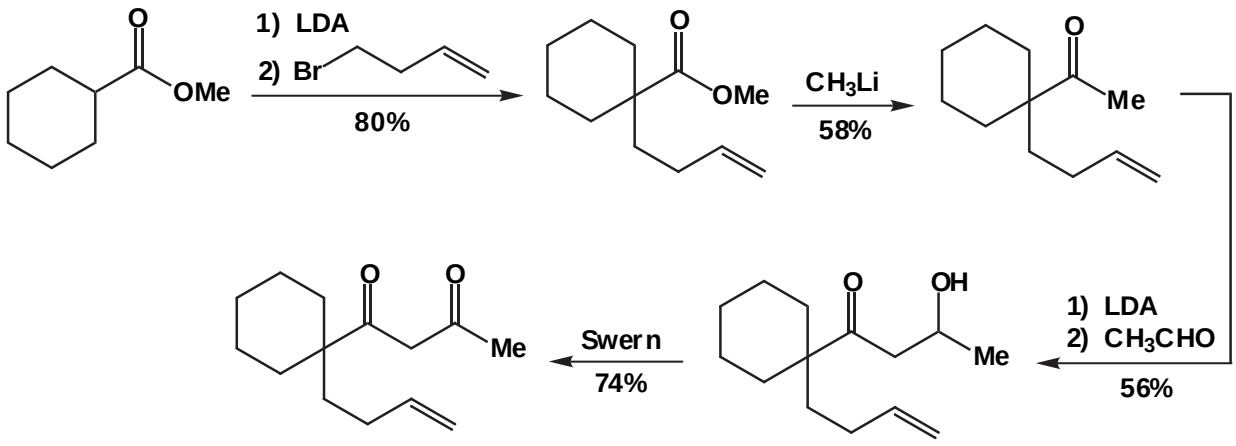
5,5-Dimethyl-1-(2-methyl-[1,3]-dioxolan-2-yl)-6-hepten-2-ol (1.26 g, 5.50 mmol) was oxidized employing a procedure analogous to that used to synthesize 6,6-dimethyl-9-decene-3,5-dione and was

purified by chromatography ($SiO_2$; hexanes–ether = 25:1) to give 7,7-dimethyl-8-nonene-2,4-dione (0.55 g, 55%) as a yellow oil.

**For 5,5-Dimethyl-1-(2-methyl-[1,3]dioxolan-2-yl)-6-hepten-2-ol:** $^1$H NMR: δ 5.78-5.71 (m, 1 H), 4.91 (s, 1 H), 4.87 (dd, *J* = 1.6, 6.8 Hz, 1 H), 3.98 (m, 4 H), 3.84-3.78 (m, 1 H), 3.59 (s, 1 H), 1.82 (dd, *J* = 1.6, 14.8 Hz, 1 H), 1.74 (dd, *J* = 9.6, 14.8 Hz, 1 H), 1.50-1.37 (m, 2 H), 1.35 (s, 3 H), 1.34-1.22 (m, 2 H), 0.98 (s, 6 H). $^{13}$C{$^1$H} NMR: δ 148.6, 110.8, 68.9, 65.0, 64.6, 45.2, 38.5, 36.6, 32.7, 27.1, 26.9, 24.5. IR (neat, cm$^{-1}$): 3526, 3079, 2955, 2884, 1645, 1557, 1540, 1472, 1456, 1416, 1376, 1302, 1105, 1039. TLC: $R_f$ = 0.19. Anal. calcd (found) for $C_{13}H_{24}O_3$: H, 10.59 (10.47); C, 68.38 (68.19).

**For 7,7-Dimethyl-8-nonene-2,4-dione:** Enol:keto = 10:1. $^1$H NMR: δ 15.46 (s, 1 H), 5.72 (dd, *J* = 10.8, 17.4 Hz, 1 H), 5.47 (s, 1 H), 4.96 (dd, *J* = 1.6, 10.8 Hz, 1 H), 4.92 (dd, *J* = 1.6, 17.4 Hz, 1 H), 2.22-2.16 (m, 2 H), 2.03 (s, 3 H), 1.61-1.57 (m, 2 H), 1.00 (s, 6 H). $^{13}$C{$^1$H} NMR: δ 195.7, 191.0, 147.6, 111.7, 100.0, 38.2, 36.7, 34.5, 26.9, 25.1. IR (neat, cm$^{-1}$): 3082, 2997, 2961, 2928, 2869, 1728, 1711, 1620, 1454, 1416, 1362, 1285, 1239, 1160, 1127, 1001. TLC: $R_f$ = 0.48. Anal. calcd (found) for $C_{11}H_{18}O_2$: H, 9.95 (10.02); C, 72.49 (72.36).

**1-[1-(3-Butenyl)cyclohexyl]butane-1,3-dione (Table 1, entry 17, 18).** 1-[1-(3-Butenyl)cyclohexyl]butane-1,3-dione was synthesized in 19% overall yield in five steps from methyl cyclohexanecarboxylate employing the route depicted in Scheme S4.




**Scheme S4**

Methyl cyclohexanecarboxylate (8.0 g, 56.3 mmol) was added to a solution of LDA [generated from *n*-BuLi (2.5 N in hexanes, 22.5 mL, 56.3 mmol) and diisopropylamine (7.0 g, 69 mmol) in THF (60 mL) at 0 °C] over 1 h at –78 °C and the resulting solution was stirred for 30 min. To the resulting solution, a solution of 4-bromo-1-butene (8.0 g, 60 mmol) in HMPA (10 mL) was added dropwise over 30 min at –78 °C and stirred for 40 min, warmed to room temperature, and stirred for 2 h. The reaction mixture was quenched with ice (20 g) and aqueous HCl (3 N, 30 mL). The layers were separated and the aqueous layer was extracted with ether ($3 \times 50$ mL). The combined organic extracts were washed (brine), dried ($MgSO_4$), and concentrated under vacuum. Distillation of the residue (64-66 °C, 350 mTorr) gave 1-(3-butenyl)-1-carbomethoxycyclohexane (8.8 g, 80%) as a colorless oil.

A solution of methyl lithium (50 mL, 1.4 N in THF, 70 mmol) was added to a solution of 1-(3-butenyl)-1-carbomethoxycyclohexane (6.0 g, 30 mmol) in THF (40 mL) at 0 °C and stirred for 1 h. The reaction mixture was quenched with ice (20 g) and aqueous HCl (3 N, 30 mL). The layers were separated and the aqueous layer was extracted with ether ($3 \times 50$ mL). The combined organic extracts were washed (brine), dried ($MgSO_4$), and concentrated under vacuum. Chromatography of the residue ($SiO_2$; hexanes–EtOAc = 50:1) gave 1-acetyl-1-(3-butenyl)cyclohexane[11] (3.2 g, 58%) as a colorless oil.

1-Acetyl-1-(3-butenyl)cyclohexane (2.0 g, 11 mmol) was added slowly to a solution of LDA [generated from *n*-BuLi (5.5 mL, 2.5 M, 14 mmol) and diisopropylamine (1.4 g, 14 mmol) in THF (20 mL)] at –78 °C and stirred for 15 min. The resulting white suspension was treated with slow addition of acetaldehyde (0.54 g, 12 mmol) and stirred for 1 h. The resulting mixture was quenched with aqueous ammonium chloride (6 mL) at –78 °C, the layers were separated, and the aqueous layer was extracted with ether ($3 \times 50$ mL). The combined organic extracts were washed (brine), dried ($MgSO_4$), and concentrated under vacuum. Chromatography of the residue ($SiO_2$; hexanes–ether = 33:1 $\rightarrow$ 1:2) gave 1-[1-(3-butenyl)cyclohexyl]-3-hydroxybutan-1-one (1.4 g, 56%) as a colorless oil.

1-(3-Butenyl)cyclohexyl-3-hydroxybutan-1-one was oxidized employing a procedure analogous to that used to synthesize 6,6-dimethyl-9-decene-3,5-dione and was purified by chromatography ($SiO_2$; hexanes–ether = 50:1 $\rightarrow$ 25:1) to give 1-[1-(3-butenyl)cyclohexyl]-butane-1,3-dione in 74% yield as a colorless oil.

**For 1-(3-butenyl)-1-carbomethoxycyclohexane**. $^1$H NMR (300 MHz): δ 5.83 (tdd, *J* = 6.3, 10.5, 16.8 Hz, 1 H), 4.99-5.10 (m, 2 H), 3.76 (s, 3 H), 2.17 (m, 2 H), 1.99-2.06 (m, 2 H), 1.62-1.78 (m, 4 H), 1.25-1.47 (m, 6 H). $^{13}$C{$^1$H} NMR: δ 176.4, 137.8, 117.7, 50.7, 46.1, 39.0, 33.5, 27.8, 25.2, 22.5. TLC: $R_f$ = 0.66. Anal. calcd (found) for $C_{12}H_{20}O_2$: H, 10.27 (10.27); C, 73.43 (73.33).

**For 1-acetyl-1-(3-butenyl)cyclohexane**: $^1$H NMR (300 MHz): δ 5.83 (tdd, *J* = 6.6, 10.2, 16.8 Hz, 1 H), 5.00-5.10 (m, 2 H), 2.19 (s, 3 H), 2.06-2.12 (m, 2 H), 1.90-1.98 (m, 2 H), 1.61-1.68 (m, 6 H), 1.36-1.39 (m, 4 H). $^{13}$C{$^1$H} NMR (75 MHz): δ 212.8, 137.6, 113.9, 51.2, 37.4, 32.6, 27.4, 25.4, 24.6, 22.2. TLC: $R_f$ = 0.55. Anal. calcd (found) for $C_{12}H_{20}O$: H, 11.18 (11.27); C, 79.94 (79.71).

**For 1-[1-(3-butenyl)cyclohexyl]-3-hydroxy-1-butanone:** $^1$H NMR (300 MHz): δ 5.71 (tdd, *J* = 6.3, 10.2, 16.8 Hz, 1 H), 4.89-4.99 (m, 2 H), 4.12-4.20 (m, 1 H), 3.43 (br s, 1 H), 2.64 (dd, *J* = 2.7, 18.0 Hz, 1 H), 2.43 (dd, *J* = 9.0, 18.0 Hz, 1 H), 1.94-1.99 (m, 2 H), 1.77-1.86 (m, 2 H), 1.50-1.57 (m, 5 H), 1.23 (br s, 6 H), 1.17 (d, *J* = 6.3 Hz, 3 H). $^{13}$C{$^1$H} NMR (75 MHz): δ 216.5, 137.4, 114.1, 63.3, 51.2, 44.2, 37.3, 32.3, 27.4, 25.2, 22.1, 21.7. IR (neat, cm$^{-1}$): 3439, 2931, 2860, 1693. TLC: $R_f$ = 0.17. Anal. calcd (found) for $C_{14}H_{24}O_2$: H, 10.78 (10.78); C, 74.95 (74.91).

**For 1-[1-(3-butenyl)cyclohexyl]-1,3-butanedione:** Enol:keto = 10:1. $^1$H NMR: δ 16.0 (br s, 1 H), 5.73 (tdd, *J* = 6.4, 10.0, 16.8 Hz, 1 H), 5.62 (s, 1 H), 4.87-4.98 (m, 2 H), 2.07 (s, 3 H), 1.86-1.97 (m, 4 H), 1.47-1.61 (m, 5 H), 1.26-1.42 (m, 5 H). $^{13}$C{$^1$H} NMR: δ 200.0, 191.1, 138.9, 114.5, 98.1, 46.8, 39.8, 33.8, 28.3, 26.3, 25.3, 22.9. IR (neat, cm$^{-1}$): 2933, 2855, 2359, 2340, 1601, 1455. TLC: $R_f$ = 0.69. Anal. calcd (found) for $C_{14}H_{24}O_2$: H, 9.97 (9.81); C, 75.63 (75.46).

**Alkenyl β-Keto Esters**

**Isopropyl 4,4-dimethyl-3-oxo-7-octenoate (18)**. Isopropyl acetate (1.43 g, 14.0 mmol) was added to a solution of LDA [generated from *n*-BuLi and diisopropylamine] in THF (70 mL) at –78 °C and the resulting solution was stirred for 30 min at –78 °C. Methyl 2,2-dimethyl-5-hexenoate (1.09 g, 7.0 mmol) was added dropwise and the mixture was stirred at room temperature overnight. The reaction mixture was quenched with saturated aqueous $NH_4Cl$, the layers were separated and the aqueous layer was extracted with ether (3 × 50 mL). The combined organic extracts were washed (brine), dried ($MgSO_4$), and

concentrated under vacuum. Chromatography of the residue ($SiO_2$; hexanes–EtOAc = 20:1) gave isopropyl 4,4-dimethyl-3-oxo-7-octenoate (1.08 g, 68%) as a yellow oil. TLC (hexanes–EtOAc = 10:1): $R_f$ = 0.50. Enol:keto = 1:7. $^1$H NMR (keto tautomer): δ 5.76 (tdd, *J* = 6.4, 10.4, 16.8 Hz, 1 H), 5.05 (septet, *J* = 6.4 Hz, 1 H), 4.88-5.03 (m, 2 H), 3.46 (s, 2 H), 1.92-1.98 (m, 2 H), 1.58-1.62 (m, 2 H), 1.24 (d, *J* = 6.0 Hz, 6 H), 1.14 (s, 6 H). $^{13}$C{$^1$H} NMR (keto tautomer): δ 208.1, 167.5, 138.4, 115.1, 69.1, 48.3, 44.8, 39.2, 29.2, 24.3, 22.3. IR (neat, cm$^{-1}$): 2977, 2934, 1741, 1705, 1640, 1469, 1410, 1107, 1053, 913. Anal. calcd (found) for $C_{13}H_{22}O_3$: C, 68.99 (69.61); H, 9.80 (9.65).

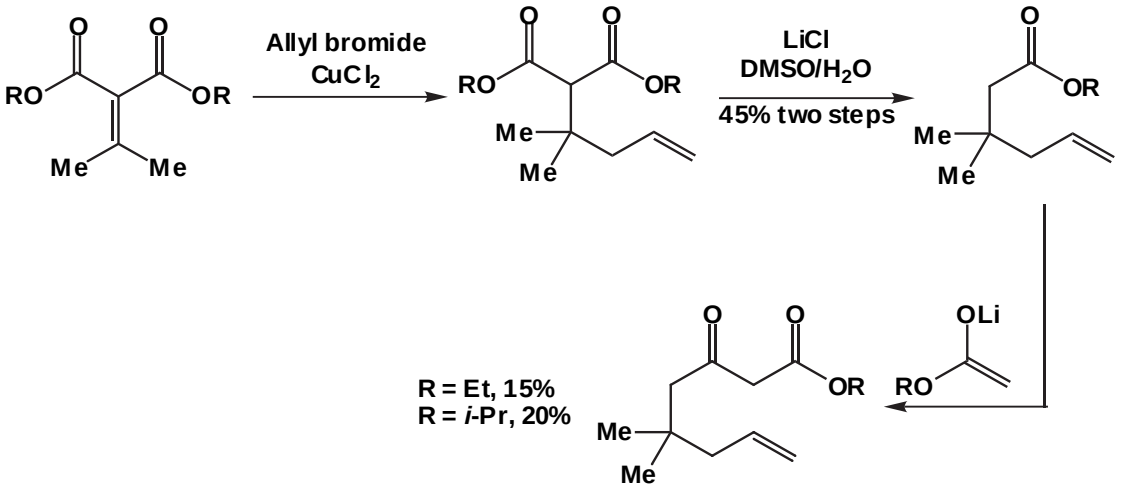
**Methyl 4,4-dimethyl-3-oxo-7-octenoate (Table 2, entry 2)**. A solution of methyl isobutyrylacetate (0.72 g, 5.0 mmol) in THF (3 mL) was added to a suspension of NaH (120 mg, 5.0 mmol) in THF (20 mL) at 0 °C, stirred for 15 min, and cooled to –78 °C. To this, a solution of *n*-BuLi in hexane (2.5 M, 2.0 mL 5.0 mmol) was added slowly and the resulting mixture was stirred at –78 °C for 15 min. The reaction mixture was then warmed to 0 °C, treated with 4-bromo-1-butene (0.81 g, 6.0 mmol), and stirred overnight. The resulting mixture was quenched with saturated aqueous $NH_4Cl$, the layers were separated, and the aqueous layer was extracted with ether (3 × 30 mL). The combined organic extracts were washed (brine), dried ($MgSO_4$), and concentrated under vacuum. Chromatography of the residue ($SiO_2$; hexanes–EtOAc = 20:1) gave methyl 4,4-dimethyl-3-oxo-7-octenoate (251 mg, 25%) as a yellow oil. TLC (hexanes–EtOAc = 10:1): $R_f$ = 0.43. Enol:keto = 1:5. $^1$H NMR (keto tautomer): δ 5.76 (tdd, *J* = 6.4, 10.2, 17.0 Hz, 1 H), 4.92-5.03 (m, 2 H), 3.72 (s, 3 H), 3.52 (s, 2 H), 1.92-1.98 (m, 2 H), 1.56-1.65 (m, 2 H), 1.15 (s, 6 H). $^{13}$C{$^1$H} NMR (keto tautomer): δ 207.9, 168.5, 138.4, 115.2, 52.6, 48.4, 44.4, 39.1, 29.2, 24.3. IR (neat, cm$^{-1}$): 2971, 1750, 1706, 1436, 1145, 912. Anal. calcd (found) for $C_{11}H_{18}O_3$: C, 66.64 (66.40); H, 9.15 (9.44).

**Ethyl 4,4-dimethyl-3-oxo-7-octenoate (Table 2, entry 3)**. Ethyl 4,4-dimethyl-3-oxo-7-octenoate was isolated in 18% yield as a yellow oil from the reaction of methyl isobutyrylacetate and 4-bromo-1-butene employing a procedure similar to that used to synthesize methyl 4,4-dimethyl-3-oxo-7-octenoate. TLC (hexanes–EtOAc = 10:1): $R_f$ = 0.33. Enol:keto = 3:7. $^1$H NMR (keto tautomer): δ 5.76 (tdd, *J* = 6.4, 10.4, 16.8 Hz, 1 H), 4.88-5.03 (m, 2 H), 4.18 (q, *J* = 7.2 Hz, 2 H), 3.50 (s, 2 H), 1.91-1.98 (m, 2 H), 1.55-1.63 (m, 2 H), 1.28 (t, *J* = 7.2 Hz, 3 H), 1.12 (s, 6 H). $^{13}$C{$^1$H} NMR (keto tautomer): δ

208.0, 168.0, 138.4, 115.1, 61.5, 48.3, 44.5, 39.1, 29.2, 24.3, 14.4. IR (neat, $cm^{-1}$): 2975, 1748, 1707, 1643, 1617, 1414, 1365, 1216, 1037, 913. Anal. calcd (found) for $C_{12}H_{20}O_3$: C, 67.89 (67.75); H, 9.50 (9.41).

**Ethyl 3-[1-(3-butenyl)cyclohexyl]-3-oxo-propionate (Table 2, entry 4)**. Ethyl acetate (0.88 g, 10.0 mmol) was added to a solution of LDA [generated from *n*-BuLi and diisopropylamine] in THF (50 mL) at –78 °C and the resulting solution was stirred for 30 min. The resulting solution was treated with 1-(3-butenyl)-1-carbomethoxycyclohexane (0.98 g, 5.0 mmol), stirred at room temperature overnight, and quenched with saturated aqueous $NH_4Cl$. The layers were separated and the aqueous layer was extracted with ether (3 × 50 mL). The combined organic extracts were washed (brine), dried ($MgSO_4$), and concentrated under vacuum. Chromatography of the residue ($SiO_2$; hexanes–EtOAc = 20:1) gave ethyl 3-[1-(3-butenyl)cyclohexyl]-3-oxo-propionate (150 mg, 10%) as a colorless oil. TLC (hexanes–EtOAc = 10:1): $R_f$ = 0.33. Enol:keto = 2:8. $^1$H NMR (keto tautomer): δ 5.75 (tdd, *J* = 6.6, 10.2, 17.0 Hz, 1 H), 4.88-5.02 (m, 2 H), 4.19 (q, *J* = 7.6 Hz, 2 H), 3.48 (s, 2 H), 1.86-1.97 (m, 4 H), 1.30-1.61 (m, 10 H), 1.27 (t, *J* = 7.2 Hz, 3 H). $^{13}$C{$^1$H} NMR (keto tautomer): δ 207.7, 168.2, 138.4, 115.1, 61.5, 52.7, 44.6, 38.0, 33.3, 28.3, 26.2, 23.0, 14.5. IR (neat, $cm^{-1}$): 2933, 2855, 1747, 1703, 1226, 1033. Anal. calcd (found) for $C_{15}H_{24}O_3$: C, 71.39 (71.68); H, 9.59 (9.83).

**Ethyl 5,5-dimethyl-3-oxo-7-octenoate (Table 2, entry 5)**. Ethyl 5,5-dimethyl-3-oxo-7-octenoate was isolated in 7% overall yield from diethyl isopropylidenemalonate employing the procedure outlined in Scheme S5.




**Scheme S5**

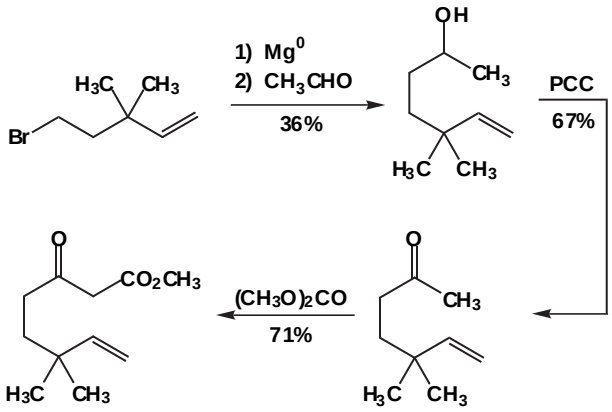
Allyl magnesium bromide (1.0 M, 30 mL, 30 mmol) was added to a suspension of CuCl (1.0 g, 10 mmol) in THF (100 mL) at –15 °C. The resulting suspension was stirred for 10 min, treated with a solution of diethyl isopropylidenemalonate (5.0 g, 25 mmol) in THF (20 mL), and stirred for 1 h at –15 °C and then 1 h at room temperature. The resulting mixture was quenched with saturated aqueous $NH_4Cl$, the layers were separated, and the aqueous layer was extracted with ether ($3 \times 100$ mL). The combined organic extracts were washed (brine), dried ($MgSO_4$), and concentrated to give crude diethyl 2-(1,1-dimethyl-3-butenyl)malonate[12] as a light yellow oil that was used in the subsequent step without further purification. A solution of crude diethyl 2-(1,1-dimethyl-3-butenyl)malonate, LiCl (2.10 g, 50 mmol) and $H_2O$ (1.0 mL) in DMSO (50 mL) was refluxed overnight and poured into brine (100 mL). The layers were separated and the aqueous layer was extracted with hexanes ($5 \times 50$ mL). Chromatography of the residue ($SiO_2$; hexanes–EtOAc = 25:1) gave ethyl 3,3-dimethyl-5-hexenoate[12] (1.93 g, 45% two steps) as a light yellow oil.

Ethyl acetate (0.47 g, 5.3 mmol) was added to a solution of LDA [generated from *n*-BuLi and diisopropylamine] in THF (30 mL) at –78 °C and the resulting solution was stirred for 30 min at –78 °C. 3,3-Dimethyl-5-hexenoate (0.90 g, 5.3 mmol) was added dropwise and the resulting mixture was stirred at room temperature overnight. The resulting mixture was quenched with saturated aqueous $NH_4Cl$, the layers were separated, and the aqueous layer was extracted with ether ($3 \times 30$ mL). The combined organic

extracts were washed (brine), dried ($MgSO_4$), and concentrated under vacuum. Chromatography of the residue ($SiO_2$; hexanes–EtOAc = 20:1) gave ethyl 5,5-dimethyl-3-oxo-7-octenoate (169 mg, 15%) as a light yellow oil. TLC (hexanes–EtOAc = 10:1): $R_f$ = 0.36. Enol:keto = 4:6. $^1$H NMR (keto tautomer): δ 5.76 (tdd, *J* = 7.6, 10.4, 16.8 Hz, 1 H), 4.92-5.08 (m, 2 H), 4.18 (q, *J* = 7.2 Hz, 2 H), 3.38 (s, 2 H), 2.41 (s, 1 H), 2.09 (dd, *J* = 7.6, 24.0 Hz, H), 2.05 (s, 1 H), 1.27 (t, *J* = 7.2 Hz, 3 H), 1.01 (s, 6 H). $^{13}$C{$^1$H} NMR (keto tautomer): δ 202.5, 167.5, 135.1, 118.1, 61.6, 60.2, 51.6, 46.5, 34.1, 27.5, 14.4. IR (neat, cm$^{-1}$): 2961, 1745, 1717, 1234, 1036, 917. Anal. calcd (found) for $C_{12}H_{20}O_3$: C, 67.89 (67.59); H, 9.50 (9.47).

**Isopropyl 5,5-dimethyl-3-oxo-7-octenoate (Table 2, entry 6)**. Isopropyl 5,5-dimethyl-3-oxo-7-octenoate was isolated in 20% yield as a yellow oil from reaction of 3,3-dimethyl-5-hexenoate and isopropyl acetate employing a procedure similar to that used to synthesize ethyl 5,5-dimethyl-3-oxo-7-octenoate (Scheme S5). TLC (hexanes–EtOAc = 10:1): $R_f$ = 0.42. Enol:keto = 3:7. $^1$H NMR (keto tautomer): δ 5.76 (tdd, *J* = 6.4, 10.2, 17.0 Hz, 1 H), 4.88-5.09 (m, 3 H), 3.34 (s, 2 H), 2.40 (s, 1 H), 2.07 (dd, *J* = 7.6, 22.8 Hz, H), 2.04 (s, 1 H), 1.24 (d, *J* = 6.0 Hz, 6 H), 1.01 (s, 6 H). $^{13}$C{$^1$H} NMR (keto tautomer): δ 202.6, 167.1, 135.2, 118.1, 69.2, 67.6, 51.9, 46.5, 34.0, 27.54 22.0. IR (neat, cm$^{-1}$): 2985, 1741, 1716, 1639, 1240, 1106, 913. Anal. calcd (found) for $C_{13}H_{22}O_3$: C, 68.99 (69.62); H, 9.80 (10.16).

**Methyl 6,6-dimethyl-3-oxo-7-octenoate (Table 2, entry 7)**. Methyl 6,6-dimethyl-3-oxo-7-octenoate was synthesized in 17% overall yield in three steps from 5-bromo-3,3-dimethyl-1-pentene employing the procedure outlined in Scheme S6.




**Scheme S6**

5-Bromo-3,3-dimethyl-1-pentene (7.60 g, 43.0 mmol) was added dropwise to a suspension of Mg powder (1.32 g, 55 mmol) in ether (100 mL) and the resulting suspension was refluxed for 20 min and cooled to room temperature. Acetaldehyde (4.40 g, 100 mmol) was added dropwise and the resulting mixture was stirred at room temperature for 5 h and quenched with saturated aqueous $NH_4Cl$. The layers were separated and the aqueous layer was extracted with ether ($3 \times 100$ mL). The combined organic extracts were washed (brine), dried ($MgSO_4$), and concentrated under vacuum. Chromatography of the residue ($SiO_2$; hexanes–EtOAc = 10:1) gave 5,5-dimethyl 6-hepten-2-ol (2.20 g, 36%) as a light yellow oil.

5,5-dimethyl 6-hepten-2-ol (2.20 g, 15.5 mmol) was added rapidly to a suspension of PCC (6.5 g, 30 mmol) in $CH_2Cl_2$ (50 mL) at room temperature and stirred for 1 h. The resulting black suspension was diluted with ether (100 mL) and decanted. The black solid that remained was extracted with ether ($2 \times 50$ mL). The combined organic extracts were concentrated and distilled under vacuum to give 5,5-dimethyl-6-hepten-2-one[13] (1.45 g, 67%) as a colorless oil. 5,5-Dimethyl-6-hepten-2-one (0.70 g, 5.0 mmol) was added dropwise over 10 min to a suspension of NaH (0.30 g, 12.5 mmol), dimethyl carbonate (1.05 mL, 12.5 mmol) and methanol (1 drop) in THF (20 mL) at room temperature. The resulting mixture was stirred at room temperature for 7 h and quenched with 1N HCl at 0 °C. The layers were separated and the aqueous layer was extracted with ether ($3 \times 30$ mL). The combined organic extracts were washed (brine), dried ($MgSO_4$), and concentrated under vacuum. Chromatography of the residue ($SiO_2$; hexanes–EtOAc = 25:1) gave methyl 6,6-dimethyl-3-oxo-7-octenoate (0.71 g, 71%) as a colorless oil.

**For 5,5-dimethyl-6-hepten-2-ol:** TLC (hexanes–EtOAc = 2:1): $R_f$ = 0.50. $^1$H NMR: δ 5.74 (dd, $J$ = 11.2, 17.2 Hz, 1 H), 4.87-4.93 (m, 2 H), 3.72 (septet, $J$ = 6.0 Hz, 1 H), 1.20-1.41 (m, 5 H), 1.17 (d, $J$ = 6.0 Hz, 3 H), 0.98 (s, 6 H). $^{13}$C{$^1$H} NMR: δ 148.6, 110.9, 69.1, 38.9, 36.6, 34.6, 27.1, 23.9. IR (neat, cm$^{-1}$): 3344, 2962, 1122, 909. HRMS calcd (found) for $C_9H_{18}O$ ($M^+$–OH): 125.1331 (125.1328).

**For methyl 6,6-dimethyl-3-oxo-7-octenoate:** TLC (hexanes–EtOAc = 10:1): $R_f$ = 0.32. Enol:keto = 1:10. $^1$H NMR (keto tautomer): δ 5.68 (dd, $J$ = 10.8, 17.6 Hz, 1 H), 4.88-4.97 (m, 2 H), 3.72 (s, 3 H), 3.43 (s, 2 H), 2.42-2.46 (m, 2 H), 1.57-1.61 (m, 2 H), 0.98 (s, 6 H). $^{13}$C{$^1$H} NMR (keto

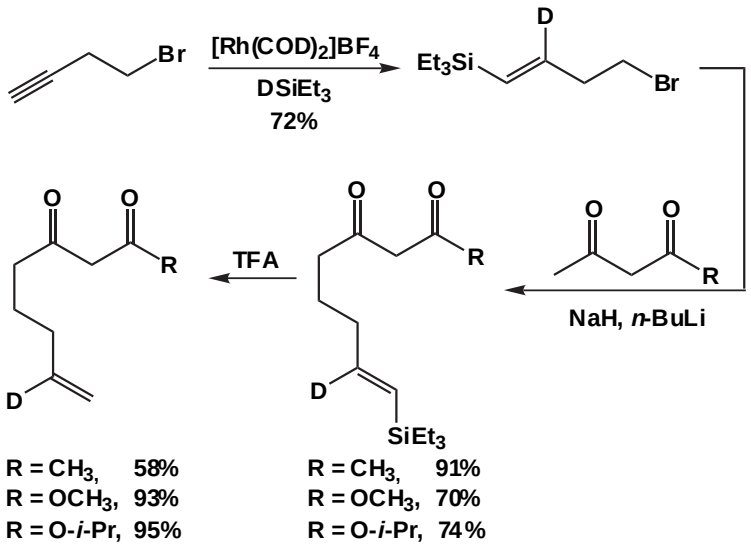
tautomer): δ 203.3, 168.0, 147.4, 111.8, 52.6, 49.4, 39.2, 36.4, 35.6, 26.9. IR (neat, $cm^{-1}$): 2959, 1748, 1716, 1437, 1321, 913. Anal. calcd (found) for $C_{11}H_{18}O_3$: C, 66.64 (66.46); H, 9.15 (9.29).

**Methyl *cis*-4,4-dimethyl-3-oxo-7-nonenoate (Table 2, entry 8)**. Methyl *cis*-4,4-dimethyl-3-oxo-7-nonenoate was isolated in 15% yield as a light green oil from the reaction of methyl isobutyrylacetate and *cis*-5-bromo-2-pentene employing a procedure similar to that used to synthesize methyl 4,4-dimethyl-3-oxo-7-octenoate. TLC (hexanes–EtOAc = 10:1): $R_f$ = 0.43. Enol:keto = 10:1. $^1$H NMR (keto tautomer): δ 5.27-5.47 (m, 2 H), 3.72 (s, 3 H), 3.53 (s, 2 H), 1.88-1.96 (m, 2 H), 1.58 (d, $J$ = 6.4 Hz, 3 H), 1.55 (q, $J$ = 6.2 Hz, 2 H), 1.15 (s, 6 H). $^{13}$C{$^1$H} NMR (keto tautomer): δ 207.9, 168.5, 129.9, 124.8, 52.6, 48.5, 44.3, 39.8, 24.3, 22.5, 13.0. IR (neat, $cm^{-1}$): 2970, 1751, 1707, 1618, 1438, 1218. Anal. calcd (found) for $C_{12}H_{20}O_3$: C, 67.89 (67.55); H, 9.50 (9.63).

**Methyl *trans*-4,4-dimethyl-3-oxo-7-nonenoate (Table 2, entry 9)**. Methyl *trans*-4,4-dimethyl-3-oxo-7-nonenoate was isolated in 42% yield as a light green oil from the reaction of methyl isobutyrylacetate and *trans*-5-bromo-2-pentene employing a procedure similar to that used to synthesize methyl 4,4-dimethyl-3-oxo-7-octenoate. TLC (hexanes–EtOAc = 10:1): $R_f$ = 0.27. Enol:keto = 1:10. $^1$H NMR (keto tautomer): δ 5.30-5.51 (m, 2 H), 3.72 (s, 3 H), 3.52 (s, 2 H), 1.83-1.90 (m, 2 H), 1.61 (d, $J$ = 6.0 Hz, 3 H), 1.55 (m, 2 H), 1.13 (s, 6 H). $^{13}$C{$^1$H} NMR (keto tautomer): δ 208.0, 168.5, 130.8, 125.8, 52.6, 48.4, 44.4, 39.9, 28.1, 24.3, 18.2. IR (neat, $cm^{-1}$): 2958, 1751, 1708, 1618, 1438, 1217. Anal. calcd (found) for $C_{12}H_{20}O_3$: C, 67.89 (67.58); H, 9.50 (9.60).

**Deuterated Isotopomers**

**8-Deuterio-8-nonene-2,4-dione (4-8-$d_1$).** Compound **4**-8-$d_1$ was synthesized in 38% overall from 4-bromo-1-butyne and $DSiEt_3$ yield employing the procedure depicted in Scheme S7.




**Scheme S7**

***trans*-4-Bromo-2-deuterio-1-triethylsilyl-1-butene.** A solution of $[Rh(COD)_2]BF_4$ (12 mg, 0.03 mmol), $PPh_3$ (16 mg, 0.06 mmol), $DSiEt_3$ (0.53 mL, 3.3 mmol), and 4-bromo-1-butyne (399 mg, 3.0 mmol) in acetone (5 mL) was stirred at room temperature for 1 h. The resulting solution was concentrated under vacuum and chromatographed ($SiO_2$; hexanes–EtOAc = 100:1) to give *trans* 4-bromo-2-deuterio-1-triethylsilyl-1-butene (540 mg, 72%) as a colorless oil. TLC (hexanes–EtOAc = 10:1): $Rf$ = 0.84. $^1$H NMR: δ 5.69 (m, 1 H), 3.42 (t, $J$ = 7.2 Hz, 2 H), 2.68 (t, $J$ = 7.2 Hz, 2 H), 0.93 (t, $J$ = 8.0 Hz, 9 H), 0.56 (t, $J$ = 8.0 Hz, 6 H). $^{13}$C{$^1$H} NMR: δ 143.9 (t, $J$ = 23.5 Hz), 130.1, 40.1, 32.2, 7.7, 3.7. IR (neat, cm$^{-1}$): 2952, 2873, 1596, 1016, 720. HRMS calcd (found) for $C_{10}H_{20}DBrSi$ ($M^+$): 249.0658 (249.0675).

***trans*-8-Deuterio-9-triethylsilyl-8-nonene-2,4-dione.** A solution of 2,4-pentadione (0.41 mL, 4.0 mmol) in THF (3 mL) was added to a suspension of NaH (100 mg, 4.2 mmol) in THF (10 mL) at 0 °C, and stirred for 15 min. A solution *n*-BuLi in hexane (2.5 M, 1.7 mL 4.2 mmol) was added dropwise to the resulting solution at –78 °C and stirred for 15 min. *trans*-4-Bromo-2-deuterio-1-triethylsilyl-1-butene (490 mg, 2.0 mmol) was added to the resulting mixture at 0 °C, stirred overnight, and quenched with saturated aqueous $NH_4Cl$. The layers were separated and the aqueous layer was extracted with ether (3 × 20 mL). The combined organic extracts were washed (brine), dried ($MgSO_4$), and concentrated under vacuum. Chromatography of the residue ($SiO_2$; hexanes–EtOAc = 50:1) gave *trans*-8-deuterio-9-

triethylsilyl-8-nonene-2,4-dione (477 mg, 91%) as a yellow oil. TLC (hexanes–EtOAc = 10:1): $R_f$ = 0.43. Enol:keto = 7:1. $^1$H NMR: δ 15.49 (s, 1 H), 5.57 (m, 1 H), 5.48 (s, 1 H), 2.27 (t, *J* = 7.6 Hz, 2 H), 2.16 (t, *J* = 7.4 Hz, 2 H), 2.05 (s, 3 H), 1.72 (quint, *J* = 7.6 Hz, 2 H), 0.92 (t, *J* = 7.8 Hz, 9 H), 0.54 (q, *J* = 8.0 Hz, 6 H). $^{13}$C{$^1$H} NMR: δ 194.4, 191.7, 147.1 (t, *J* = 23.0 Hz), 127.3, 100.2, 37.9, 36.5, 25.3, 25.0, 7.7, 4.0. IR (neat, cm$^{-1}$): 2952, 2873, 1615, 777, 719. HRMS calcd (found) for $C_{15}H_{27}DO_2Si$ ($MH^+$): 270.1998 (270.1998).

**8-Deuterio-8-nonene-2,4-dione (4-8-*d*$_1$).** Trifluoroacetic acid (0.61 mL, 8.0 mmol) was added to a solution of *trans*-8-deuterio-9-triethylsilyl-8-nonene-2,4-dione (430 mg, 1.6 mmol) in $CH_2Cl_2$ (9 mL), stirred for 1 h, and quenched with saturated aqueous $NaHCO_3$. The layers were separated and the aqueous layer was extracted with ether (3 × 20 mL). The combined organic extracts were washed (brine), dried ($MgSO_4$), and concentrated under vacuum. Chromatography of the residue ($SiO_2$; hexanes–EtOAc = 100:1) gave 8-deuterio-8-nonene-2,4-dione (145 mg, 58%) as a yellow oil. TLC (hexanes–EtOAc = 10:1): $R_f$ = 0.40. Enol:keto = 3:1. $^1$H NMR: δ 15.47 (s, 1 H), 5,47 (m, 1 H), 5.00 (m, 1 H), 4.96 (m, 1 H), 2.26 (t, *J* = 7.8 Hz, 2 H), 2.06 (t, *J* = 7.4 Hz, 2 H), 2.03 (s, 3 H), 1.68 (quint, *J* = 7.6 Hz, 2 H). $^{13}$C{$^1$H} NMR: δ 194.2, 191.7, 137.7 (t, *J* = 23.1 Hz), 115.4, 100.1, 37.8, 33.2, 25.2, 25.0. IR (neat, cm$^{-1}$): 2933, 1616, 1351, 913, 778. HRMS calcd (found) for $C_9H_{13}DO_2$ ($MH^+$): 155.1134 (155.1052).

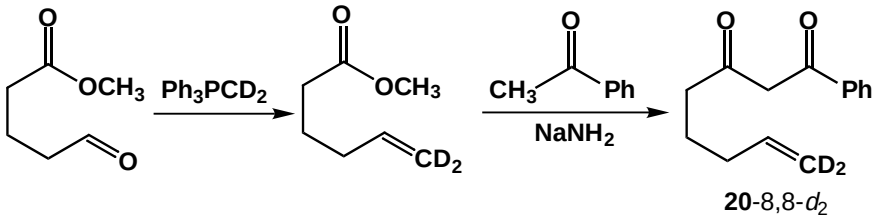
**Methyl 7-deuterio-3-oxo-7-octenoate (15-7-*d*$_1$).** Compound **15**-7-$d_1$ was isolated in 47% yield as a colorless oil employing procedures analogous to that used to synthesize **4**-8-$d_1$ (Scheme S7).

**For Methyl 7-deuterio-8-triethylsilyl-3-oxo-7-octenoate:** TLC (hexanes–EtOAc = 10:1): $R_f$ = 0.25. Enol:keto = 1:10. $^1$H NMR (keto tautomer): δ 4.55 (m, 1 H), 3.72 (s, 3 H), 3.43 (s, 2 H), 2.52 (t, *J* = 7.4 Hz, 2 H), 2.12 (t, *J* = 7.2 Hz, 2 H), 1.70 (quint, *J* = 7.4 Hz, 2 H), 0.91 (t, *J* = 8.0 Hz, 9 H), 0.53 (q, *J* = 8.0 Hz, 6 H). $^{13}$C{$^1$H} NMR (keto tautomer): δ 202.9, 167.9, 147.0 (t, *J* = 22.9 Hz), 127.3, 52.6, 49.4, 42.5, 36.1, 22.6, 7.6, 4.0. IR (neat, cm$^{-1}$): 2952, 2873, 1750, 1718, 1237, 1014, 721. HRMS calcd (found) for $C_{15}H_{27}DO_3Si$ ($M^+$ – Et): 256.1478 (256.1481).

**For 15-7-*d*$_1$:** TLC (hexanes–EtOAc = 10:1): $R_f$ = 0.25. Enol:keto = 1:10. $^1$H NMR (keto tautomer): δ 4.95-5.00 (m, 2 H), 3.73 (s, 3 H), 3.47 (s, 2 H), 2.54 (t, *J* = 7.4 Hz, 2 H), 2.04 (t, *J* = 7.2 Hz, 2 H), 1.68 (quint, *J* = 7.4 Hz, 2 H). $^{13}$C{$^1$H} NMR (keto tautomer): δ 203.8, 168.5, 137.6 (t, *J* = 23.0

Hz), 115.7, 52.9, 49.3, 42.5, 32.9, 22.7. IR (neat, $cm^{-1}$): 2952, 1746, 1714, 1438, 1322, 1167, 915. HRMS calcd (found) for $C_9H_{13}DO_3$ ($M^+$): 171.1005 (171.1004).

**8,8-Dideuterio-1-phenyl-7-octene-1,3-dione (20-8,8-$d_2$).** Compound **20**-8,8-$d_2$ was synthesized in 5 % overall yield in two steps from methyl 5-oxopentanoate[14] employing the procedure outlined in Scheme S8.




**Scheme S8**

*n*-BuLi (2.5 M, 3.8 mL, 9.5 mmol) was added to a suspension of $Ph_3PCD_3Br$ (3.42 g, 9.5 mmol) in THF (50 mL) at 0 °C, stirred for 1 h, and treated with a solution of methyl 5-oxopentanoate in THF (10 mL). The resulting mixture was stirred at room temperature for 2.5 h and quenched with saturated $NH_4Cl$ solution. The layers were separated and the aqueous layer was extracted with ether (3 × 50 mL). The combined organic extracts were washed (brine), dried ($MgSO_4$), and concentrated under vacuum. Chromatography of the residue ($SiO_2$; hexanes–EtOAc = 30:1) gave methyl 6,6-dideuterio-5-hexenoate (120 mg, 10%, 83% D incorporation) as a light yellow oil. Acetophenone (180 mg, 1.5 mmol) and methyl 6,6-dideuterio-5-hexenoate (200 mg, 1.5 mmol) were added sequentially to a suspension of $NaNH_2$ (117 mg, 3.0 mmol) in ether (5 mL). The resulting mixture was refluxed overnight, quenched with 1 N HCl solution. The layers were separated and the aqueous layer was extracted with ether (3 × 10 mL). The combined organic extracts were washed (brine), dried ($MgSO_4$), and concentrated under vacuum. Chromatography of the residue ($SiO_2$; hexanes–EtOAc = 50:1) gave **11**-8,8-$d_2$ (164 mg, 50%, 83% D incorporation) as a light yellow oil.

**For methyl 6,6-dideuterio-5-hexenoate:** TLC (hexanes–EtOAc = 10:1): $R_f$ = 0.46. $^1$H NMR: δ 5.75 (m, 1 H), 3.65 (s, 3 H), 2.31 (t, $J$ = 6.8 Hz, 2 H), 2.08 (q, $J$ = 7.2 Hz, 2 H), 1.72 (quint, $J$ = 7.6 Hz, 2

H). $^{13}C\{^{1}H\}$ NMR: δ 174.4, 137.8, 51.8, 33.6, 33.3, 24.3. HRMS calcd (found) for $C_7H_{10}O_2D_2$ ($M^+$): 130.0961 (130.0958).

**For 20-8,8-$d_2$:** TLC (hexanes–EtOAc = 50:1): $R_f$ = 0.64. $^{1}H$ NMR (enol tautomer): δ 16.18 (s, 1 H), 7.90-7.87 (m, 2 H), 7.54-7.43 (3 H), 6.17 (s, 1 H), 5.81 (m, 1 H), 5.08-4.99 (m, 0.28 H), 2.44 (t, *J* = 7.0 Hz, 2 H), 2.15 (q, *J* = 7.0 Hz, 2 H), 1.80 (quint, *J* = 7.2 Hz, 2 H). $^{13}C\{^{1}H\}$ NMR (enol tautomer): δ 197.0, 183.8, 137.9, 135.4, 132.6, 128.9, 127.3, 96.5, 38.8, 33.4, 25.2.

**Isopropyl 7-deuterio-4,4-dimethyl-3-oxo-7-octenoate (18-7-$d_1$).** Compound **18**-7-$d_1$ was isolated in 51% yield as a light brown oil employing procedures analogous to that used to synthesize **4**-8-$d_1$ (Scheme S7).

**For Isopropyl 7-deuterio-8-triethylsilyl-4,4-dimethyl-3-oxo-7-octenoate:** Yellow oil. TLC (hexanes–EtOAc = 5 : 1): $R_f$ = 0.71. $^{1}H$ NMR (keto tautomer): δ 5.53-5.56 (m, 1 H), 5.04 (septet, *J* = 6.0 Hz, 1 H), 3.47 (s, 2 H), 2.00-2.04 (m, 2 H), 1.57-1.63 (m, 2 H), 1.24 (d, *J* = 6.0 Hz, 6 H), 1.15 (s, 6 H), 0.91 (t, *J* = 8.0 Hz, 9 H), 0.53 (q, *J* = 8.0 Hz, 6 H). $^{13}C\{^{1}H\}$ NMR (keto tautomer): δ 208.1, 167.6, 148.1 (t, *J* = 23.1 Hz), 126.5, 69.1, 48.3, 44.8, 39.0, 32.1, 24.3, 22.0, 7.7, 3.8. IR (neat, $cm^{-1}$): 2952, 2874, 1744, 1708, 1610, 1215, 1108. HRMS calcd (found) for $C_{19}H_{35}DO_3Si$ ($M^+$ - Et): 312.2104 (312.2091).

**For 18-7-$d_1$:** Light brown oil. TLC (hexanes–EtOAc = 10 : 1): $R_f$ = 0.50. $^{1}H$ NMR (keto tautomer): δ 5.07 (septet, *J* = 6.2 Hz, 1 H), 4.87-4.95 (m, 2 H), 3.47 (s, 2 H), 1.91-1.97 (m, 2 H), 1.55-1.63 (m, 2 H), 1.27 (d, *J* = 6.0 Hz, 6 H), 1.15 (s, 6 H). $^{13}C\{^{1}H\}$ NMR (keto tautomer): δ 208.1, 167.6, 138.8 (t, *J* = 23.2 Hz), 114.4, 69.1, 48.3, 44.8, 40.0, 29.2, 24.3, 22.0. IR (neat, $cm^{-1}$): 2978, 2942, 1743, 1706, 1639, 1615, 1221, 1108. HRMS calcd (found) for $C_{13}H_{21}DO_3$ ($M^+$): 227.1631 (227.1624).

**Cyclohexenones**

**2-Acetyl-3-deuteriomethyl-2-cyclohexenone (5-$CH_2D$)**. The sample studied by NMR spectroscopy consisted of a 55:45 $d_1$:$d_0$ isotopomers by MS analysis. $^{1}H$ NMR ($d_1$ isotopomer): δ 2.35-2.41 (m, 4 H), 2.31 (s, 3 H), 1.97 (quint, *J* = 6.4 Hz, 2 H), 1.91 (t, *J* = 2.2 Hz, 2 H, $CH_2D$). $^{13}C\{^{1}H\}$ NMR ($d_1$ isotopomer): δ 204.7, 197.2, 160.2, 140.0, 37.7, 32.5, 32.0, 21.7 (t, *J* = 22.5 Hz, isotopic shift = 220 ppb).

**2-Benzoyl-3-dideuteriomethyl-2-cyclohexenone (21-3-$CHD_2$)**. The sample studied by NMR spectroscopy consisted of a 60:40 $d_2$:$d_1$ isotopomers by MS analysis. $^1$H NMR: δ 7.85-7.42 (m, 5 H), 2.51 (t, $J$ = 6.8 Hz, 2 H), 2.49 (t, $J$ = 6.4 Hz, 2 H), 2.13 (quint, $J$ = 6.0 Hz, 2 H), 1.84 (m, 1.25 H). $^{13}$C{$^1$H} NMR: δ 197.5, 197.2, 160.1, 138.1, 137.1, 134.0, 129.4, 129.1, 37.6, 32.2, 22.4.

**2-Carbomethoxy-3-methylcyclohexanone (16).**[15] TLC: $R_f$ = 0.35. $^1$H NMR: δ 3.76 (s, 3 H), 3.05 (d, $J$ = 11.2 Hz, 1 H), 2.49-2.44 (m, 1 H), 2.32-2.24 (m, 2 H), 2.08-2.01 (m, 1 H), 1.95-1.89 (m, 1 H), 1.79-1.57 (m, 2 H), 1.02 (d, $J$ = 6.4 Hz, 3 H). $^{13}$C{$^1$H} NMR: δ 206.3, 170.5, 65.4, 52.3, 41.2, 37.0, 32.7, 25.3, 21.2.

**2-Carbomethoxy-3-deuteriomethylcyclohexanone (16-$CH_2D$).** The sample studied by NMR spectroscopy consisted of >95% $d_1$ isotopomer by MS analysis. $^1$H NMR (keto tautomer): δ 3.76 (s, 3 H), 3.05 (d, $J$ = 11.4 Hz, 1 H), 2.44-2.49 (m, 1 H), 2.24-2.32 (m, 2 H), 2.01-2.08 (m, 1 H), 1.89-1.95 (m, 1 H), 1.57-1.79 (m, 2 H), 1.02 (1:1:1 td, $J$ = 2.2, 6.8 Hz, 3 H). $^{13}$C{$^1$H} NMR (keto tautomer): δ 206.3, 170.5, 65.4, 52.3, 41.2, 37.0, 32.7, 25.3, 21.0 (t, $J$ = 19.2 Hz, isotopic shift = 251 ppb).

**2-Carbomethoxy-6-deuterio-3-methylcyclohexanone (16-6-$d_1$).** The sample studied by NMR spectroscopy consisted of a 68:32 $d_1$:$d_0$ isotopomers by MS analysis. $^1$H NMR (keto tautomer): δ 3.76 (s, 3 H), 3.05 (d, $J$ = 11.2 Hz, 1 H), 2.44-2.49 (m, 1 H), 2.24-2.32 (m, 2 H), 2.01-20.8 (m, 1 H), 1.89-1.95 (m, 1 H), 1.57-1.79 (m, 2 H), 10.2 (d, $J$ = 6.4 Hz, 3 H). $^{13}$C{$^1$H} NMR (keto tautomer): δ 206.3, 170.5, 65.3, 52.2, 40.8 (t, $J$ = 18.6 Hz, IS = 334 ppb), 36.9, 32.6, 25.3, 21.2. The position of the deuterium atom in **16**-6-$d_1$ was established by $^1$H-$^{13}$C COSY analysis.

**2-Carbomethoxy-3-methyl-2-cyclohexenone (17).**[16] $^1$H NMR: δ 3.81 (3, 3 H), 2.43-2.37 (m, 4 H), 2.02 (m, 2 H), 1.98 (s, 3 H). $^{13}$C{$^1$H} NMR: δ 195.2, 167.5, 160.8, 133.2, 52.4, 37.0, 31.8, 22.4, 21.8.

**2-Carboisopropoxy-3,6,6-trimethyl-2-cyclohexenone (19).** Yellow oil, (73%). TLC (hexanes–EtOAc = 2:1): $R_f$ = 0.66. $^1$H NMR: δ 5.16 (heptet, $J$ = 6.2 Hz, 1 H), 2.36 (t, $J$ = 6.2 Hz, 2 H), 1.93 (s, 3 H), 1.81 (t, $J$ = 6.0 Hz, 2 H), 1.29 (d, $J$ = 6.4 Hz, 6 H), 1.11 (s, 6 H). $^{13}$C{$^1$H} NMR: δ 200.2, 167.2, 157.3, 132.2, 69.0, 40.4, 35.6, 29.0, 24.3, 22.1, 22.0. IR (neat, cm$^{-1}$): 2978, 2916, 1726, 1669, 1318, 1265, 1237, 1106, 1060. Anal. calcd (found) for $C_{13}H_{20}O_3$: C, 69.61 (69.61); H, 8.99 (9.09).

**2-Carboisopropoxy-3-deuteriomethyl-6,6-dimethyl-2-cyclohexenone (19-$CH_2D$)**. The sample studied by NMR spectroscopy consisted of a 57:43 $d_1$:$d_0$ isotopomers by MS analysis. $^1$H NMR: δ 5.15 (septet, $J$ = 6.2 Hz, 1 H), 2.35 (t, $J$ = 6.2 Hz, 2 H), 1.91 (t, $J$ = 2.4 Hz, 2 H), 1.80 (t, $J$ = 6.0 Hz, 2 H), 1.28 (d, $J$ = 6.4 Hz, 6 H), 1.10 (s, 6 H). $^{13}$C{$^1$H} NMR: δ 200.2, 167.2, 157.3, 132.2, 69.0, 40.3, 35.5, 29.0, 24.3, 21.9 (t, $J$ = 18.6 Hz, isotopic shift = 364 ppb).

**2-(2,2-Dimethylpropionyl)-3-methyl-2-cyclohexenone (Table 1, entries 2 and 3).** TLC: $R_f$ = 0.13. $^1$H NMR: δ 2.37 (t, $J$ = 6.0 Hz, 2 H), 2.33 (t, $J$ = 6.0 Hz, 2 H), 1.98 (quint, $J$ = 6.0 Hz, 2 H), 1.81 (s, 3 H), 1.13 (s, 9 H). $^{13}$C{$^1$H} NMR: δ 215.2, 197.2, 156.9, 14.01, 44.7, 37.3, 31.8, 27.2, 22.5, 22.0. IR (neat, cm$^{-1}$): 2970, 2925, 1699, 1661, 1423. Anal. calcd (found) for $C_{12}H_{18}O_2$: H, 9.34 (9.37); C, 74.19 (74.26).

**3,6,6-Trimethyl-2-propionyl-2-cyclohexenone (Table 1, entries 7 and 8)**. TLC: $R_f$ = 0.22. $^1$H NMR: δ 2.51 (q, $J$ = 7.2 Hz, 2 H), 2.34 (t, $J$ = 6.0 Hz, 2 H), 1.82 (s, 3 H), 1.77 (t, $J$ = 6.0 Hz, 2 H), 1.07 (s, 6 H), 1.03 (t, $J$ = 7.6 Hz, 3 H). $^{13}$C{$^1$H} NMR: δ 208.2, 202.2, 157.0, 138.1, 40.5, 37.2, 35.4, 29.3, 24.1, 21.5, 7.9. IR (neat, cm$^{-1}$): 2975, 2926, 1704, 1661. Anal. calcd (found) for $C_{12}H_{18}O_2$: H, 9.34 (9.36); C, 74.19 (73.99).

**2-Isobutyryl-3,6,6-trimethyl-2-cyclohexenone (Table 1, entries 9 and 10)**. TLC: $R_f$ = 0.36. $^1$H NMR: δ 2.79 (septet, $J$ = 6.8 Hz, 1 H), 2.33-2.36 (m, 2 H), 1.81 (s, 3 H), 1.77 (t, $J$ = 6.0 Hz, 2 H), 1.07 (s, 6 H), 1.03 (d, $J$ = 7.2 Hz, 6 H). $^{13}$C{$^1$H} NMR: δ 211.2, 202.4, 157.7, 137.6, 41.1, 40.5, 35.4, 29.3, 24.1, 21.8, 17.9. IR (neat, cm$^{-1}$): 2970, 2930, 1697, 1660. Anal. calcd (found) for $C_{13}H_{20}O_2$: H, 9.68 (9.61); C, 74.96 (74.97).

**2-(2,2-Dimethylpropionyl)-3,6,6-trimethyl-2-cyclohexenone (Table 1, entries 11 and 12).** White needles, mp 55-56 °C. TLC: $R_f$ = 0.27. $^1$H NMR: δ 2.32 (t, $J$ = 6.0 Hz, 2 H), 1.78 (t, $J$ = 6.0 Hz, 2 H), 1.77 (s, 3 H), 1.10 (s, 9 H), 1.07 (s, 6 H). $^{13}$C{$^1$H} NMR: δ 215.5, 202.3, 154.9, 138.6, 44.7, 40.6, 35.7, 29.0, 27.3, 24.2, 22.2. IR (neat, cm$^{-1}$): 3011, 2970, 1740, 1439, 1369, 1215. Anal. calcd (found) for $C_{11}H_{16}O_2$: H, 9.97 (9.89); C, 75.63 (75.71).

**2-Cyclohexanecarbonyl-3,6,6-trimethyl-2-cyclohexenone (Table 1, entry 13)**. White powder, mp 60-61 °C. TLC: $R_f$ = 0.27. $^1$H NMR: δ 2.50-2.52 (m, 1 H), 2.36 (t, $J$ = 6.0 Hz, 2 H), 1.82-

1.86 (m, 2 H), 1.83 (s, 3 H), 1.79 (t, *J* = 6.0 Hz, 2 H), 1.72 (br d, *J* = 6.8 Hz, 2 H), 1.62 (br d, *J* = 7.2 Hz, 1 H), 1.05-1.31 (m, 5 H), 1.10 (s, 6 H). $^{13}C\{^{1}H\}$ NMR: δ 210.7, 202.5, 157.6, 137.8, 50.9, 40.6, 35.5, 29.4, 28.2, 24.2, 21.9. IR (neat, $cm^{-1}$): 3024, 2971, 1729, 1375. Anal. calcd (found) for $C_{16}H_{24}O_2$: H, 9.74 (9.89); C, 77.38 (77.26).

**3,6-Dimethyl-2-propionyl-2-cyclohexenone (Table 1, entries 14 and 15)**. $^{1}H$ NMR: δ 2.55 (q, *J* = 7.2 Hz, 2 H), 2.24-2.46 (m, 3 H), 1.98 (qd, *J* = 4.4, 13.2 Hz, 1 H), 1.80 (s, 3 H), 1.80-1.86 (m, 1 H), 1.05 (d, *J* = 6.8 Hz, 3 H), 1.00 (t, *J* = 7.6 Hz, 3 H). $^{13}C\{^{1}H\}$ NMR: δ 208.0, 199.7, 158.3, 139.3, 40.9, 37.4, 31.7, 30.0, 21.6, 15.1, 7.8. IR (neat, $cm^{-1}$): 2974, 2934, 1700, 1661, 1376. TLC: $R_f$ = 0.24. Anal. calcd (found) for $C_{11}H_{16}O_2$: H, 8.95 (9.00); C, 73.30 (73.15).

**2-Acetyl-3,4,4-trimethyl-2-cyclohexenone (Table 1, entry 16).** Tan solid, mp 51-53 °C. TLC: $R_f$ = 0.22. $^{1}H$ NMR: δ 2.48 (d, *J* = 6.8 Hz, 1 H), 2.46 (d, *J* = 6.8 Hz, 1 H), 2.29 (s, 3 H), 1.86 (d, *J* = 6.8 Hz, 2 H), 1.83 (s, 3 H), 1.19 (s, 6 H). $^{13}C\{^{1}H\}$ NMR: δ 205.8, 196.9, 164.7, 139.5, 37.0, 36.0, 34.7, 32.1, 26.5, 16.8. IR (neat, $cm^{-1}$): 2964, 2920, 2869, 1709, 1666, 1607, 1547, 1468, 1422, 1376, 1354, 1333, 1308, 1280, 1211, 1162. Anal. calcd (found) for $C_{11}H_{16}O_2$: H, 8.95 (8.98); C, 73.30 (73.26).

**2-Acetyl-3-methyl-spiro[5.5]-2-undecen-1-one (Table 1, entries 17 and 18).** TLC: $R_f$ = 0.24. $^{1}H$ NMR: δ 2.35 (t, *J* = 6.0 Hz, 2 H), 2.28 (s, 3 H), 1.89 (s, 3 H), 1.87 (t, *J* = 6.0 Hz, 2 H), 1.76-1.69 (m, 2 H), 1.66-1.59 (m, 2 H), 1.55-1.32 (m, 6 H). $^{13}C\{^{1}H\}$ NMR: δ 205.0, 156.7, 43.5, 31.7, 31.6, 30.1, 29.0, 26.1, 21.8, 21.4. IR (neat, $cm^{-1}$): 2925, 2861, 1698, 1659, 1447. Anal. calcd (found) for $C_{14}H_{20}O_2$: H, 9.15 (9.28); C, 76.33 (76.49).

**2-Carbomethoxy-3,6,6-trimethyl-2-cyclohexenone (Table 2, entry 2)**. Yellow oil, 69%. TLC (hexanes–EtOAc = 2:1): $R_f$ = 0.50. $^{1}H$ NMR: δ 3.80 (s, 3 H), 2.38 (t, *J* = 6.2 Hz, 2 H), 1.94 (s, 3 H), 1.81 (t, *J* = 6.6 Hz, 2 H), 1.11 (s, 6 H). $^{13}C\{^{1}H\}$ NMR: δ 200.3, 168.0, 158.5, 131.7, 52.4, 40.4, 35.5, 29.1, 24.3, 22.2. IR (neat, $cm^{-1}$): 2959, 2922, 1734, 1667, 1266, 1231, 1129. Anal. calcd (found) for $C_{11}H_{16}O_3$: C, 67.32 (67.17); H, 8.22 (8.12).

**2-Carboethoxy-3,6,6-trimethyl-2-cyclohexenone (Table 2, entry 3)**. Yellow oil. TLC (hexanes–EtOAc = 2:1): $R_f$ = 0.64. $^{1}H$ NMR: δ 4.27 (q, *J* = 7.2 Hz, 2 H), 2.37 (t, *J* = 6.2 Hz, 2 H), 1.94 (s, 3 H), 1.81 (t, *J* = 6.5 Hz, 2 H), 1.30 (t, *J* = 7.2 Hz, 3 H), 1.11 (s, 6 H). $^{13}C\{^{1}H\}$ NMR: δ 200.3, 167.6,

157.9, 131.9, 61.4, 40.4, 35.5, 29.0, 24.3, 22.1, 14.5. IR (neat, $cm^{-1}$): 2976, 2922, 1730, 1669, 1318, 1262, 1235, 1129, 1061. Anal. calcd (found) for $C_{12}H_{18}O_3$: C, 68.54 (68.53); H, 8.63 (8.74).

**2-Carbomethoxy-3-methyl-spiro[5.5]-2-undecen-1-one (Table 2, entry 4)**. Colorless oil, 67%. TLC (hexanes–EtOAc = 10:1): $R_f$ = 0.18. $^1$H NMR: δ 4.27 (t, $J$ = 7.2 Hz, 2 H), 2.33 (t, $J$ = 6.0 Hz, 2 H), 1.92 (s, 3 H), 1.89 (t, $J$ = 6.2 Hz, 2 H), 1.36-1.76 (m, 10 H), 1.30 (t, $J$ = 7.0 Hz, 3 H). $^{13}$C{$^1$H} NMR: δ 200.7, 167.7, 156.9, 132.3, 61.4, 43.4, 31.8, 30.3, 28.5, 26.2, 21.8, 14.5. IR (neat, $cm^{-1}$): 2924, 2859, 1730, 1667, 1447, 1311, 1237, 1089, 1021. Anal. calcd (found) for $C_{15}H_{22}O_3$: C, 71.97 (71.68); H, 8.63 (8.57).

**2-Carbomethoxy-3,5,5-trimethyl-2-cyclohexenone (Table 2, entry 5)**. Colorless oil, 42%. TLC (hexanes–EtOAc = 10:1): $R_f$ = 0.07. $^1$H NMR: δ 4.30 (q, $J$ = 7.2 Hz, 2 H), 2.28 (s, 2 H), 2.26 (s, 2 H), 1.97 (s, 3 H), 1.32 (t, $J$ = 7.2 Hz, 3 H), 1.05 (s, 6 H). $^{13}$C{$^1$H} NMR: δ 195.6, 167.2, 158.1, 132.5, 61.5, 50.5, 46.2, 33.3, 28.5, 22.6, 14.6. IR (neat, $cm^{-1}$): 2976, 2922, 1730, 1669, 1318, 1262, 1235, 1129, 1061. Anal. calcd (found) for $C_{12}H_{18}O_3$: C, 68.54 (68.53); H, 8.63 (8.74).

**2-Carboisopropoxy-3,5,5-trimethyl-2-cyclohexenone (Table 2, entry 6)**. Yellow oil, 50%. TLC (hexanes–EtOAc = 10:1): $R_f$ = 0.07. $^1$H NMR: δ 5.18 (septet, $J$ = 6.2 Hz, 1 H), 2.27 (s, 2 H), 2.25 (s, 2 H), 1.96 (s, 3 H), 1.30 (d, $J$ = 6.4 Hz, 6 H), 1.04 (s, 6 H). $^{13}$C{$^1$H} NMR: δ 195.6, 166.7, 157.4, 132.7, 69.1, 50.9, 46.1, 33.3, 28.6, 22.4, 22.1. IR (neat, $cm^{-1}$): 2961, 1729, 1670, 1372, 1315, 1240, 1108, 1065. Anal. calcd (found) for $C_{13}H_{20}O_3$: C, 69.61 (67.76); H, 8.99 (9.04).

**2-Carbomethoxy-3,4,4-trimethyl-2-cyclohexenone (Table 2, entry 7)**. Yellow oil, 35%. TLC (hexanes–EtOAc = 2:1): $R_f$ = 0.70. $^1$H NMR: δ 3.79 (s, 3 H), 2.40 (t, $J$ = 6.0 Hz, 2 H), 2.21 (q, $J$ = 7.6 Hz, 2 H), 1.82 (t, $J$ = 6.2 Hz, 2 H), 1.12 (t, $J$ = 7.6 Hz, 3 H), 1.11 (s, 6 H). $^{13}$C{$^1$H} NMR: δ 200.7, 168.1, 163.2, 131.0, 52.4, 40.5, 35.7, 29.4, 26.2, 24.3, 12.6. IR (neat, $cm^{-1}$): 2970, 1735, 1670, 1264, 1212, 1132. Anal. calcd (found) for $C_{12}H_{18}O_3$: C, 68.54 (68.23); H, 8.63 (8.57).

**2-Carbomethoxy-3-ethyl-6,6-dimethyl-2-cyclohexenone (Table 2, entries 8 and 9)**. Yellow oil, 65%. TLC (hexanes–EtOAc = 2:1): $R_f$ = 0.43. $^1$H NMR: δ 3.80 (s, 3 H), 2.49 (t, $J$ = 6.8 Hz, 2 H), 1.89 (s, 3 H), 1.86 (t, $J$ = 7.4 Hz, 2 H), 1.19 (s, 6 H). $^{13}$C{$^1$H} NMR: δ 195.1, 168.2, 166.1, 133.0, 52.5,

36.9, 35.9, 34.3, 26.5, 17.6. IR (neat, $cm^{-1}$): 2961, 1736, 1671, 1243,1060, 1005. Anal. calcd (found) for $C_{11}H_{16}O_3$: C, 67.32 (67.26); H, 8.22 (8.23).

**References**


[1] M. A. Andres, T-C. T. Chang, C-W. F. Cheng, L. V. Kapustay, K. P. Kelly, M. Zweifel, *J. Organometallics* **1984**, 3, 1479.

[2] A. M. Doherty, S. V. Ley, B. Lygo, D. J. Williams, *J. Chem. Soc., Perkin Trans.* **1984**, *1*, 1371.

[3] T. Hasegawa, F. Hojo, M. Yoshioka, *Bull. Chem. Soc. Jpn.* **1990**, *63*, 2428.

[4] R. A. Widenhoefer, B. Krzyzanowska, G. Webb-Wood, *Organometallics* **1998**, *17*, 5124.

[5] C. Spino, N. Barriault, *J. Org. Chem.* **1999**, *64*, 5292.

[6] S. Kashimura, Y. Murai, M. Ishifune, H. Masuda, M. Shimomura, H. Murase, T. Shono, *Acta. Chem. Scand.* **1999**, *53*, 949.

[7] A. B. Smith, P. A. Levenberg, *Synthesis* **1981**, *7*, 567.

[8] M. Kawashima, T. Sato, T. Fujisawa, *Tetrahedron* **1989**, *45*, 403.

[9] J. Brocard, G. Moinet, J. M. Conia, *Bull. Soc. Chim. Fr.* **1973**, *5*, 1711.

[10] I. Fleming, S. K. Ghosh, *J. Chem. Soc., Perkin Trans. 1.* **1998**, *17*, 2733.

[11] T. Pei, X. Wang, R. A. Widenhoefer, *J. Am. Chem. Soc.* **2003**, *125*, 648.

[12] A. L. J. Beckwith, V. W. Bowry, G. Moad, *J. Org. Chem.* **1988**, *53*, 1632.

[13] S. K. Mandal, S. R. Amin, W. E. Crowe, *J. Am. Chem. Soc.* **2001**, *123*, 6457.

[14] P. M. Gannett, D. L. Nagel, P. J. Reilly, T. Lawson, J. Sharpe, B. Toth, *J. Org. Chem.* **1988**, *53*, 1064.

[15] E. Piers, H. L. A. Tse, *Tetrahedron Lett.* **1984**, *25*, 3155.

[16] D. T. Belmont, L. A. Paquette, *J. Org. Chem.* **1985**, *50*, 4102.